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Effects of Silver and Group II Fluorides Addition to Plasma Sprayed Chromium Carbide High Temperature Solid Lubricant for Foil Gas Bearings to 650 °C

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EFFECTS OF SILVER AND GROUP II FLUORIDES ADDITION TO PLASMA SPRAYED CHROMIUM
CARBIDE HIGH TEMPERATURE SOLID LUBRICANT FOR FOIL GAS BEARINGS TO 650 °C.

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ABSTRACT

E-2317

A new self-lubricating coating composition of nickel aluminide-bonded chromium carbide formulated with silver and Group II fluorides was developed in a research program on high temperature solid lubricants. One of the proposed applications for this new coating composition is as a wide temperature spectrum solid lubricant for compliant foil gas bearings. Friction and wear properties were obtained using a foil gas bearing start/stop apparatus at temperatures from 25 to 650 °C. The journals were Inconel 718. Some were coated with the plasma-sprayed experimental coating, others with unmodified nickel aluminide/chromium carbide as a baseline for comparison. The additional components were provided to assist in achieving low friction over the temperature range of interest. Uncoated, preoxidized Inconel X-750 foil bearings were operated against these surfaces. The foils were subjected to repeated start/stop cycles under a 14-kPa (2-psi) bearing unit loading. Sliding contact occurred during lift-off and coastdown at surface velocities less than 6 m/s (3000 rpm). Testing continued until 9000 start/stop cycles were accumulated or until a rise in starting torque indicated the journal/bearing had failed. Comparison in coating performance as well as discussions of their properties and methods of application are given.

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INTRODUCTION

The compliant foil gas bearing is an ideal mechanism for supporting high speed, high performance turbine driven rotors. The main advantages of this type of bearing over conventional rolling element bearings are the longer bearing life and the potential for elimination of liquid lubrication systems. At the turbine end, high temperatures (650 °C) that would be encountered preclude the use of liquid lubricants because of short term vaporization and longer term coking of bearings. This bearing type also offers reduced power losses because of the low frictional drag of a gas film at high speeds.

Operation of a foil bearing requires a short term sliding contact of bearing against journal until hydrodynamic lift-off occurs, as well as during coastdown prior to stopping. To prevent damage to either surface, solid lubrication systems must be incorporated. These systems must be stable at high temperatures and wear resistant as well as provide low friction throughout an entire temperature range that the bearing encounters. Previous experience (1) has shown that plasma sprayed systems can be tailored to develop optimized formulations over a wide temperature spectrum.

Chromium carbide has shown promise as a thermally stable, wear resistant coating material for temperatures to 650 °C (1200 °F) (2). As with most hard coatings, chromium carbide is not effective in terms of low friction. However, with chromium carbide as a base material, solid lubricants can be added to improve low temperature frictional characteristics. In this program, the solid lubricants used were silver and a Group II fluoride binary eutectic (barium fluoride/calcium fluoride). Studies have shown that coatings with this Group II eutectic will effectively lubricate to 950 °C (1750 °F). This system in a nickel-chromium mixture has been successfully used in extreme temperature applications such as the space shuttle (3). Silver, with a low shear strength at low temperature, is included to benefit room temperature friction.

By using a combination chromium carbide (Cr_3C_2), silver, barium fluoride/calcium fluoride ($\text{BaF}_2/\text{CaF}_2$) eutectic coated journal against an uncoated, preoxidized foil bearing, the continual foil surface oxidation and replenishment of the silver- $\text{BaF}_2/\text{CaF}_2$ solid lubricants to the journal surface aid in sliding lubrication. The bonded carbide matrix acts as a lubricant reservoir with a lower thermal expansion coefficient than silver- $\text{BaF}_2/\text{CaF}_2$. Tables I and II show the composition of the constituents and their linear coefficients of thermal expansion/ $^{\circ}\text{C}$. The solid lubricants are therefore under compression during heating and exude to the surface through the porous metal material. In addition, mechanical smearing of the surface during sliding exposes the solid lubricant to the surface (4).

EXPERIMENTAL MATERIALS

Foil Bearing

The foil bearing was constructed of Inconel X-750. This nickel-chromium alloy exhibits excellent physical properties to 650 $^{\circ}\text{C}$. It retains good spring properties at elevated temperatures, important since foil bearing operation is dependent upon its flexibility. The bearing was preoxidized in air to produce a thin film of chromium oxide (Cr_2O_3) and di-iron nickel tetraoxide (NiFe_2O_4). During high temperature operation, this oxide layer assists in lubricating by providing a protective wear-resistant film on the metal surface. At high temperatures, the oxide material is replenished at the surface at least as fast as it is worn away. At lower temperatures, the oxidation rate is much slower, the protective surface becomes vulnerable to removal during sliding, and the lubricating function is much more dependent on the characteristics of the coated journal.

Test Journal

Two lubricant coating compositions were applied: (1) nickel aluminide-bonded chromium carbide only, and (2) nickel aluminide-bonded chromium carbide

with 10 wt% barium fluoride/calcium fluoride eutectic and 10 wt% silver. The latter formulation will be designated PS-200 throughout this paper. Using the unmodified coating as a baseline, a comparison can be made as to the effect of the additional constituents.

The surface to be coated was first sandblasted then plasma-sprayed with a thin bond coat (0.0075 cm) of Nichrome. This bond coat ensures the coating adhesive ability of the Cr_3C_2 -NiAl formulations at high temperature. An excess thickness of the Cr_3C_2 -NiAl coating was then plasma-sprayed over the bond coat and finish ground back to a total coating thickness (bond coat plus lubricant) of 0.025 cm.

APPARATUS AND TEST PROCEDURE

Start/Stop Bearing Test Apparatus

The bearing test machine is shown in Fig. 1. A machine of the same general design is fully described (5); a summary of the important features are given below.

The apparatus is designed to run unattended. Timer switches operate each start/stop cycle at 20-s intervals. Program time switches control the amount of time that the test is run by shutting down the heaters and electric drive motor at the end of the test sequence. A temperature control unit is used to maintain the bearing temperature at the desired level. Heating is provided by eight 500-W quartz lamps.

The test spindle is driven by a 1-hp induction motor running at 3450 rpm. A pulley ratio of 4:1 is used to provide a 13 800-rpm (28-m/s) spindle speed. The spindle is turned on for 13 s and off for 7 s (total cycle time 20 s). This time allows the bearing to fully lift-off during the start cycle and the spindle to completely stop during the stop cycle. A fiber optics impulse counter is used to count each cycle.

The bearing is mounted in a floating housing which is restrained from rotation by a torque arm that bears against a calibrated flexure plate. Deflection of this plate is a function of bearing torque and is sensed by a capacitance probe. Journal velocity and bearing torque are plotted simultaneously by a recording oscillograph. Typical velocity and torque profiles for one 20-s start/stop cycle are given in Fig. 2.

Test Bearing and Test Journal

A schematic drawing of the test bearing is given in Fig. 3. It is a partial arc 38.1-mm (1.5-in) diameter journal bearing. The bearing is of the same design as that previously reported (6). The bearing consists of a bump foil and a smooth top foil. The material of construction is Inconel X-750. The two foils are attached to a key by spot welding. The key is fitted into a keyway in the floating bearing housing and secured in place by tapered pins. The test bearing has one bump more than one-half the total number of bumps in a complete circular bearing, which results in a 186° pad arc. Rotation of the journal is into the free end of the foil. This partial arc bearing was designed specifically for coating evaluation experiments. It is capable of lift-off at about 3000 rpm (6 m/s) at a nominal radial unit load of 14 kPa (2 psi). However, it is not intended to be used as a functional journal bearing. A functional bearing would be a full circular single or multisegment bearing with a larger length-over-diameter ratio, typically 1.0.

Test Procedure

All tests were run at a maximum surface velocity of 28 m/s at 13 800 rpm and at a 14-kPa (2-psi) unit load. This is reportedly a typical radial load at startup for foil bearings in turbomachinery (7). The tests were terminated either when solid lubricant failure was indicated by a sharp rise in bearing starting torque or 9000 start/stop cycles were successfully completed. The

choice of 9000 start/stop cycles as a satisfactory coating life is approximately the number of start/stops that would be experienced by a bearing in a machine that is started on the average of five times per day over a five year period. In practice, some starts can be expected to be cold, others at intermediate bearing temperatures, and others at the maximum bearing temperature depending upon the length of time the machine is shut down before restart. Therefore a test procedure was employed at ambient temperature, two intermediate temperatures, and at a maximum temperature of 650 °C. The procedure was conducted in the following sequence:

- I. 500 start/stop cycles at 650 °C
- II(a). 250 start/stop cycles at 425 °C
- II(b). 250 Start/stop cycles at 200 °C
- III. 500 start/stop cycles at ambient

The above sequence was repeated a maximum of six times for a total of 9000 start/stop cycles.

RESULTS AND DISCUSSION

Bearing Torque

Friction coefficients for these coating combinations at various temperatures are summarized in Table 3. These coefficients were calculated directly from bearing torque measurements. The starting friction coefficients (μ_1) tabulated here will be termed "apparent" because they are higher than the true coulomb friction for the particular coating. In addition to sliding friction, other factors contribute to the friction at start (and stop). These may include dynamic elastic deformation forces acting on the highly conformable foils. Lift-off occurs at about 3000 rpm (6-m/s surface velocity). Assuming proper bearing clearance during normal "airborne" operation at 13 800 rpm (28 m/s), the computed friction coefficient (μ_2) was due to viscous shear of the lubricating gas film.

There was not a large difference in the high temperature (650 °C) starting torque between the two coatings. Computed value for μ_1 of the chromium carbide was about 0.36 and for the PS-200 coating it was about 0.29. The differences in friction became very evident at lower temperatures. Cr_3C_2 coating friction rose to 0.64 at room temperatures while it was only 0.45 for the PS-200.

Friction coefficients while airborne (μ_2) tended to remain uniformly low (less than 0.1) in all tests. There was a satisfactory gas film thickness at the relatively low speed of 13 800 rpm (28 m/s). Airborne torque tended to be higher at the elevated temperatures as compared with ambient due to the increased viscosity of the gas film.

Figures 4 and 5 give representative steady-state friction coefficients as a function of bearing temperature for Cr_3C_2 and PS-200 coatings, respectively. The friction coefficients plotted are the apparent starting friction (μ_1), friction while airborne (μ_2), and maximum apparent friction during coastdown (μ_3).

Running-in effect. - Considerably higher values of μ_1 than the steady-state values so far given were observed early in the endurance tests and may be attributed to a "running-in" mechanism at the bearing/journal contact. This is illustrated in Figs. 6 and 7, which give the starting friction coefficients for Cr_3C_2 and PS-200 for the first three programmed temperature sequences (4500 start/stop cycles). For Cr_3C_2 coating during the first 500 cycles the starting friction decreased from about 0.52 to 0.45. Friction steadily increased during the next 500 cycles at intermediate temperatures then became steady at 0.72 at room temperature. Steady-state behavior prevailed during subsequent cycles with satisfactory friction of about 0.30 generally occurring only at 650 °C. Erratic behavior was observed at the intermediate and ambient temperatures, until with extremely high

friction at room temperature ($\mu > 0.78$), the test was terminated (4500 start/stop cycles).

The PS-200 coating demonstrated a more pronounced run-in effect. The first 500 start/stop cycles at 650 °C decreased the friction from 0.52 to 0.40. At the first intermediate temperature (425 °C), the friction became even lower; afterwards as the temperature decreased, the friction increased. Interestingly, there was consistently little difference in friction between 200 and 650 °C. A marked rise occurred at room temperature, but this is still much less than the room temperature friction of the Cr_3C_2 coating. Tests were allowed to complete the programmed 9000 start/stop cycles.

There are several factors that explain the reduction of bearing starting friction as the number of start/stop cycles accumulated: (1) as-sprayed surfaces are porous and relatively rough and sliding generates a smooth surface, which is more favorable to efficient gas bearing operation; (2) this smoothing action also increases the effective radial clearance of the bearing, a factor which can be conducive to lower bearing torque; and (3) in the case of PS-200 the interspersed solid lubricants become exposed to the surface as sliding continues, decreasing the friction.

Coating Endurance

Coating endurance is defined as the number of start/stop cycles accumulated by a test bearing before a sharp rise in bearing starting torque was indicated or when foil wear exceeded 0.0025 cm. The term "coating endurance" is not completely accurate in describing these experiments since wear occurs more readily on the Inconel X-750 foil surface than on the coated journal surface. Results of the endurance tests are summarized in Table 4.

Plasma sprayed Cr_3C_2 -NiAl. - These coatings did not reach the planned 9000 start/stop cycles. Testing was terminated after 4500 start/stop cycles because of an extraordinarily high starting torque ($\mu > 0.78$) at room

temperature operation. Bearing surface damage had occurred with a substantial decrease in smooth foil thickness from the original 0.1 mm (0.004 in) to 0.075 mm (0.003 in). Figure 8 shows the amount of bearing metal removal as a function of the number of start/stop cycles. The coating itself received very little alteration with the exception of observed differences occurring during the running-in period when the wear area was smoothed. There was no measurable decrease in journal diameter, indicating no significant amount of coating material was removed. Photomicrographs and surface profiles of the foil bearing after 4500 start/stop cycles are shown in Figs. 9(a) and (b).

Oxidation of the bearing material was an important factor in the performance of this combination. At the maximum temperature, friction was relatively low, increasing as operating temperature decreased. During visual inspection of the bearing surface, it was observed that a continuous oxide film remained on the bearing after high temperature operation. This oxide film is considered to be beneficial in wear rate and the sliding friction. At lower temperatures, less oxidation was apparent, since the oxidation rate was lower, and friction and wear increased. The removal at low temperatures exceeded the formation at high temperatures and eventually the surface failed.

PS-200. - This coating combination successfully achieved 9000 start/stop cycles from ambient to 650 °C. As start/stop cycles accumulated, a thin deposit of silver began to transfer onto the foil surface. Figures 10(a) and (b) are photomicrographs and surface profiles of the foil and journal after 9000 start/stop cycles. Figure 11 shows an x-ray spectrogram of the foil surface, confirming the buildup on the foil as silver. This silver deposit increased with time. The silver acted as a thin protective coating on the foil surface; no measurable change in smooth foil thickness had occurred. Silver also acted as a low shear strength solid lubricant at low temperature, assisting in providing low contact friction.

CONCLUSIONS

A new type of formulated chromium carbide coating (PS-200) was developed and compared to an unmodified bonded chromium carbide. Both coatings were tested against uncoated, preoxidized Inconel X-750 foil bearings from ambient temperature to 650 °C. The components of the new coating were silver for achieving satisfactory low temperature friction and wear and barium fluoride/calcium fluoride eutectic for high temperature solid lubrication. The experimental program led to the following conclusions:

(1) PS-200 coatings gave much lower friction coefficients over the entire temperature range than the baseline $\text{Cr}_3\text{C}_2\text{-NiAl}$. The friction also varied less with temperature.

(2) The wear life of the foil bearing on PS-200 is more than twice that of the bonded $\text{Cr}_3\text{C}_2\text{-NiAl}$. No measurable decrease in journal diameter and smooth foil thickness was observed. Although no decrease in journal diameter occurred for the bonded $\text{Cr}_3\text{C}_2\text{-NiAl}$, considerable counterface wear of the foil bearing was obvious, because of the abrasive nature of the hard journal coating against the relatively soft foil material. The formulated coating was superior in greatly reducing the abrasiveness of the sliding contact, therefore ensuring less wear of the softer foil bearing and longer operating life.

(3) The lubricating mechanism for the $\text{Cr}_3\text{C}_2\text{-NiAl}$ coating is dependent on oxidation. When oxidation diminished, friction and wear increased. PS-200 has the additional benefits of silver and $\text{BaF}_2/\text{CaF}_2$ eutectic, which exude to the surface to provide the lubricating function. In addition, silver transfer to the foil surface aided in protecting the surface and acted as a low shear strength solid lubricant.

(4) Run-in effect for the bonded $\text{Cr}_3\text{C}_2\text{-NiAl}$ coating occurred approximately 1500 start/stop cycles into the experiment. PS-200 coating had a shorter

run-in period (approximately 500 start/stop cycles), and a obvious and beneficial change in surface topography was evident.

(5) The overall evaluation for this formulated chromium carbide coating is that it is superior to an unmodified bonded chromium carbide coating in foil bearing applications. Wear resistance and low friction throughout the entire temperature range were greatly improved by the addition of the solid lubricant components to the chromium carbide matrix.

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TABLE 1.

Component	Composition, wt %
PS-200	
Cr ₃ C ₂	48
NiAl	32
BaF ₂ /CaF ₂ eutectic	10
Ag	10
Eutectic	
BaF ₂	62
CaF ₂	38
Alloy Sponge	
Cr ₃ C ₂	60
NiAl	40

TABLE 2. - PROPERTIES

Component	Melting point, °C	Linear coefficient of expansion/°C at 650 °C
BaF ₂ ^a	1260	25.8x10 ⁻⁶
CaF ₂	1360	36.6x10 ⁻⁶
Eutectic	1020	^b 29.9x10 ⁻⁶
Ag ^c	960	24.8x10 ⁻⁶
Cr ₃ C ₂ ^d	1890	10.9x10 ⁻⁶
NiAl ^c	1640	15.8x10 ⁻⁶
Alloy sponge		^b 12.8x10 ⁻⁶

^aTouloukian, Y. S., et al, "Thermophysical Properties of Matter, Vol. 13, Thermal Expansion-Nonmetallic Solids," IFI/Plenum, 1977.

^bWeighted average $\alpha = m_1\alpha_1 + m_2\alpha_2$.

^cTouloukian, Y. S., et al, "Thermophysical Properties of Matter, Vol. 12, Thermal Expansion-Metallic Elements and Alloys," IFI/Plenum, 1977.

^dShaffer, P. T. B., "No. 1 Materials Index-Plenum Press Handbook of Higher Temperature Materials," Plenum Press, 1964.

TABLE 3. - TYPICAL FRICTION COEFFICIENTS FOR FOIL BEARING/JOURNAL
COATING COMBINATIONS

Coating combination	Temperature, °C	Friction coefficients	
		μ_1 starting	μ_2 running at 28 m/s (13 800 rpm)
1. Foil: Preoxidized I-X750 Journal: CrC-NiAl	25	0.64	0.05 to 0.08
	200	.55	.05 to .08
	425	.42	.05 to .08
	650	.36	.05 to .08
2. Foil: Preoxidized I-X750 Journal: PS-200	25	.44	0 to .04
	200	.32	.02 to .05
	425	.31	.05 to .08
	650	.29	.05 to .08

TABLE 4. - COATING DURABILITY

Coating type	Range of bearing temperatures, °C	Endurance life number of start/stop cycles to failure
Cr ₃ C ₂ -NiAl	25-650	4500
PS-200	25-650	>9000

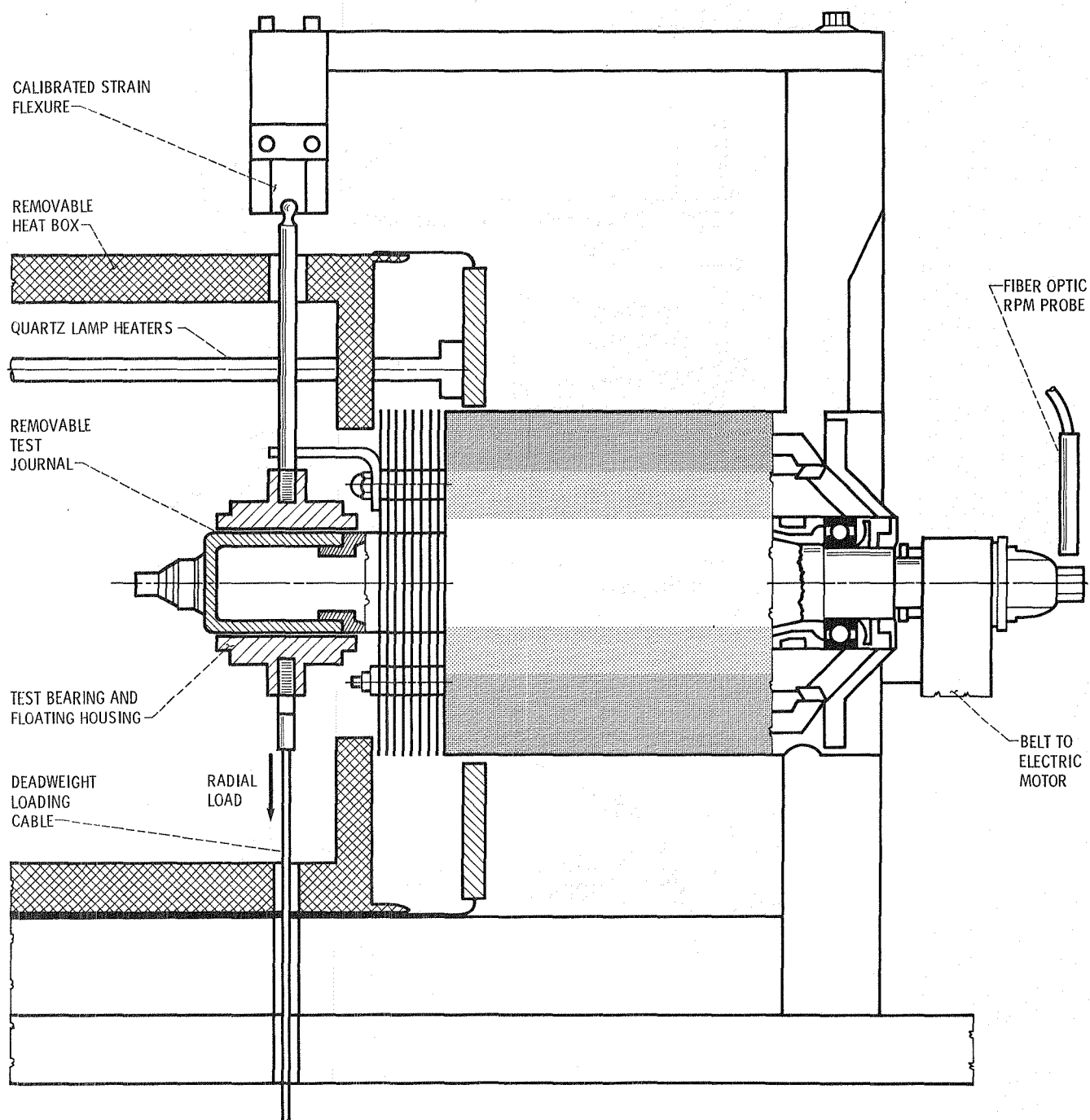


Figure 1. - Foil journal bearing materials test rig.

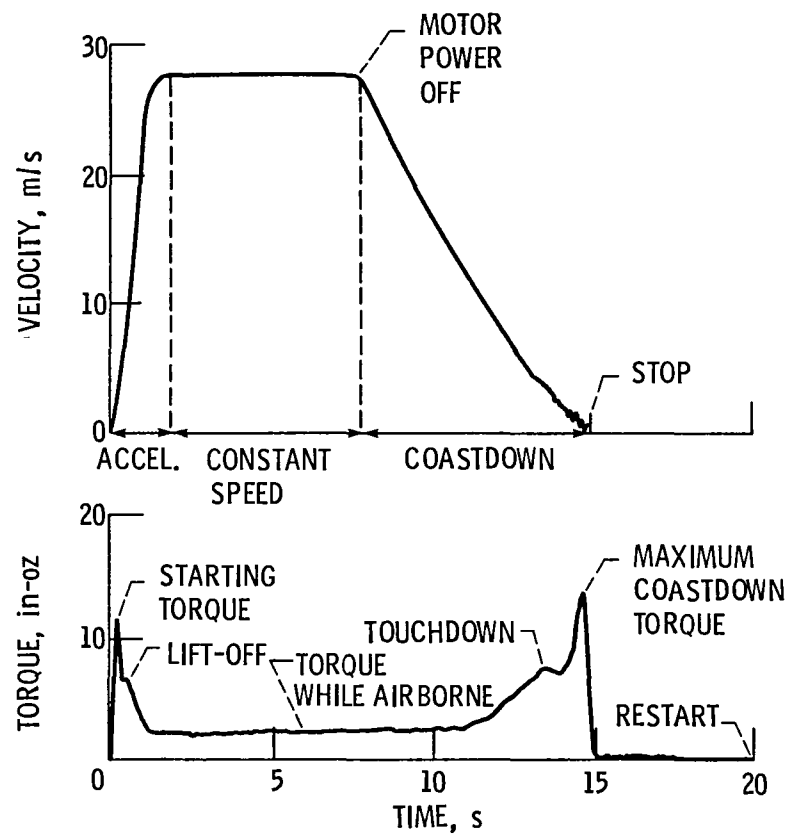


Figure 2. - Typical torque profile of a foil bearing during a single start/stop cycle.

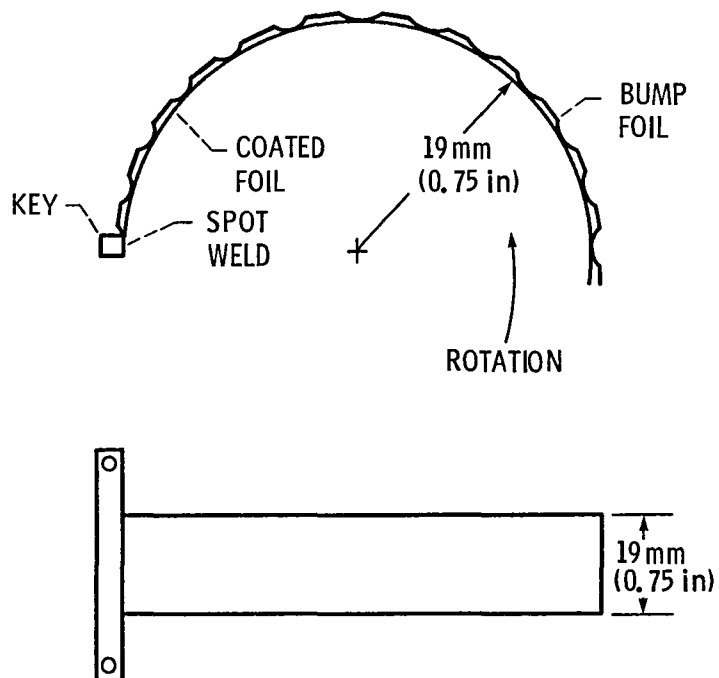


Figure 3. - Compliant foil gas test bearing for coating evaluations.

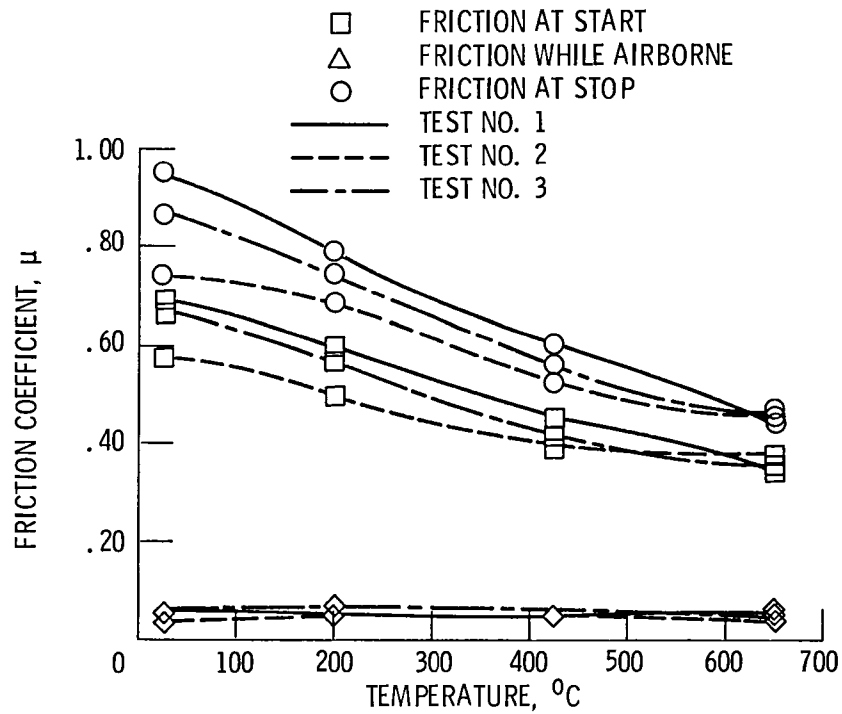


Figure 4. - Friction coefficient versus operating temperature for plasma sprayed chromium carbide coated journal and preoxidized Inconel X-750 foil bearing.

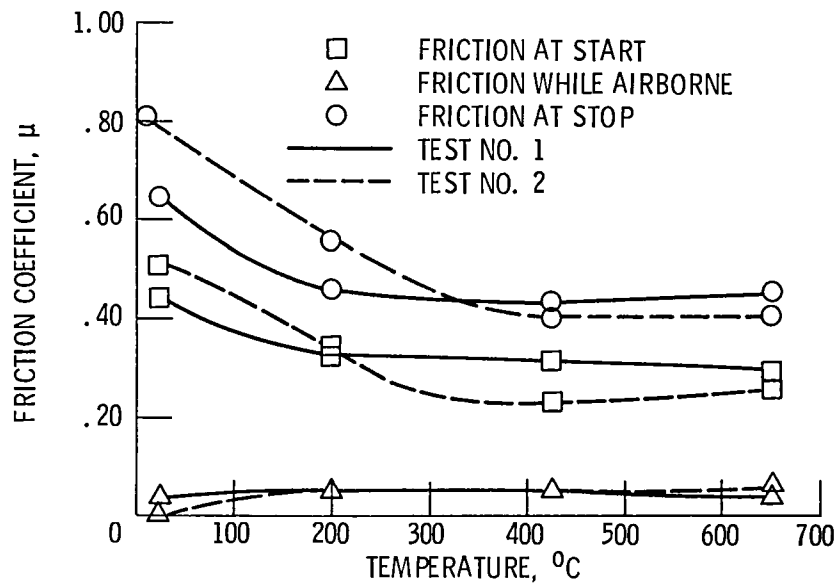


Figure 5. - Friction coefficient versus operating temperature for PS-200 (Cr_3C_2 with Ag and $\text{BaF}_2/\text{CaF}_2$ eutectic) coated journal and preoxidized Inconel X-750 foil bearing.

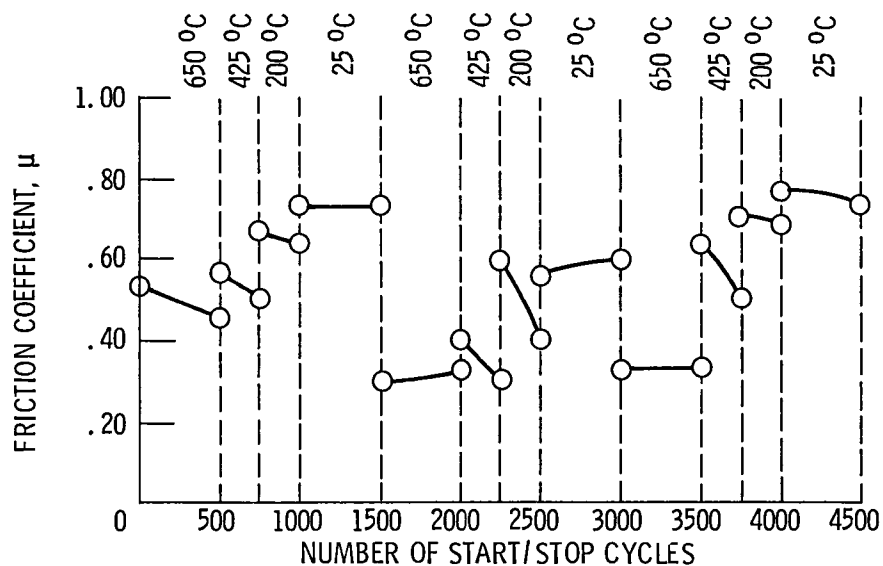


Figure 6. - Effect of run-in on starting friction for plasma sprayed CrC coated journal and preoxidized Inconel X-750 foil bearing.

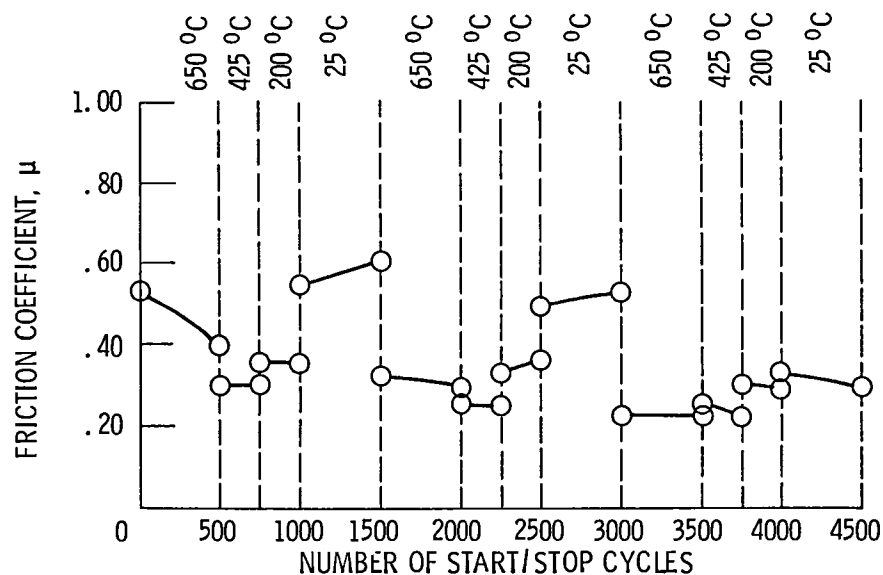


Figure 7. - Effect of run-in on starting friction for PS-200 (Cr_3C_2 with Ag and $\text{BaF}_2/\text{CaF}_2$ eutectic) coated journal and preoxidized Inconel X-750 foil bearing.

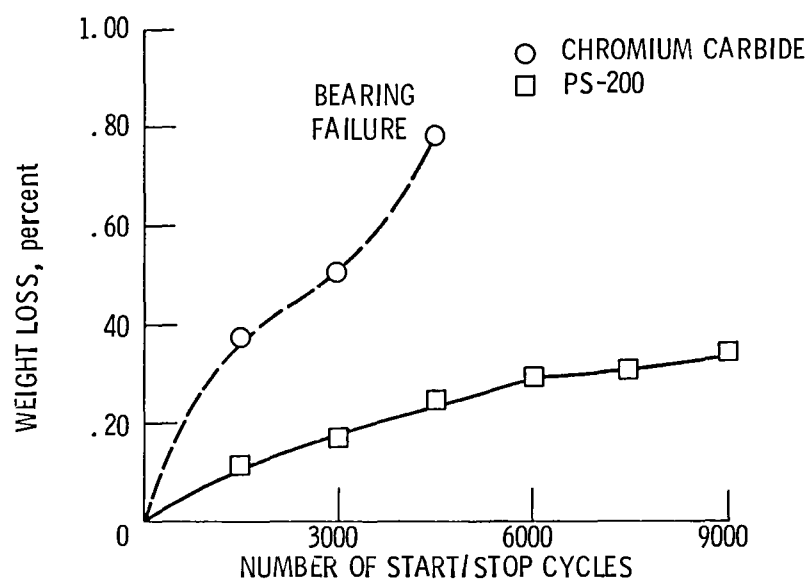


Figure 8. - Comparisons of wear profiles of preoxidized Inconel X-750 foil bearing as run against plasma sprayed chromium carbide and PS-200 coated journals.

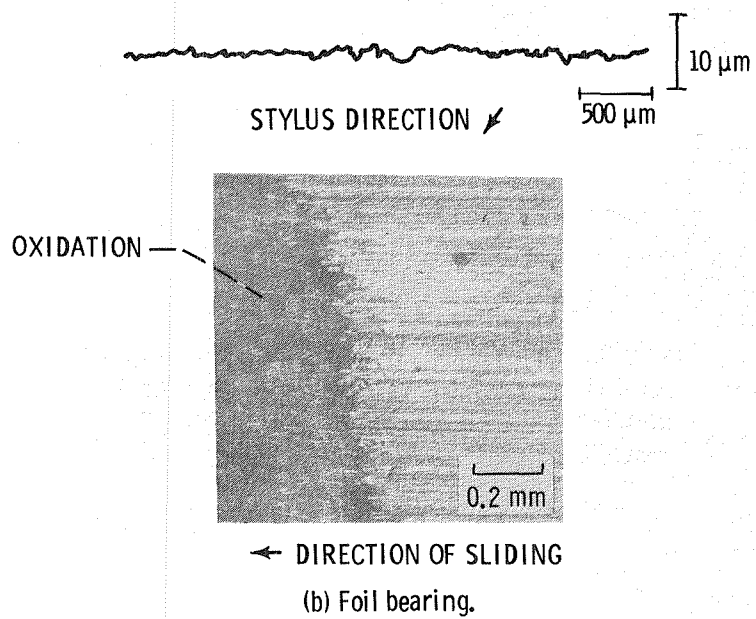
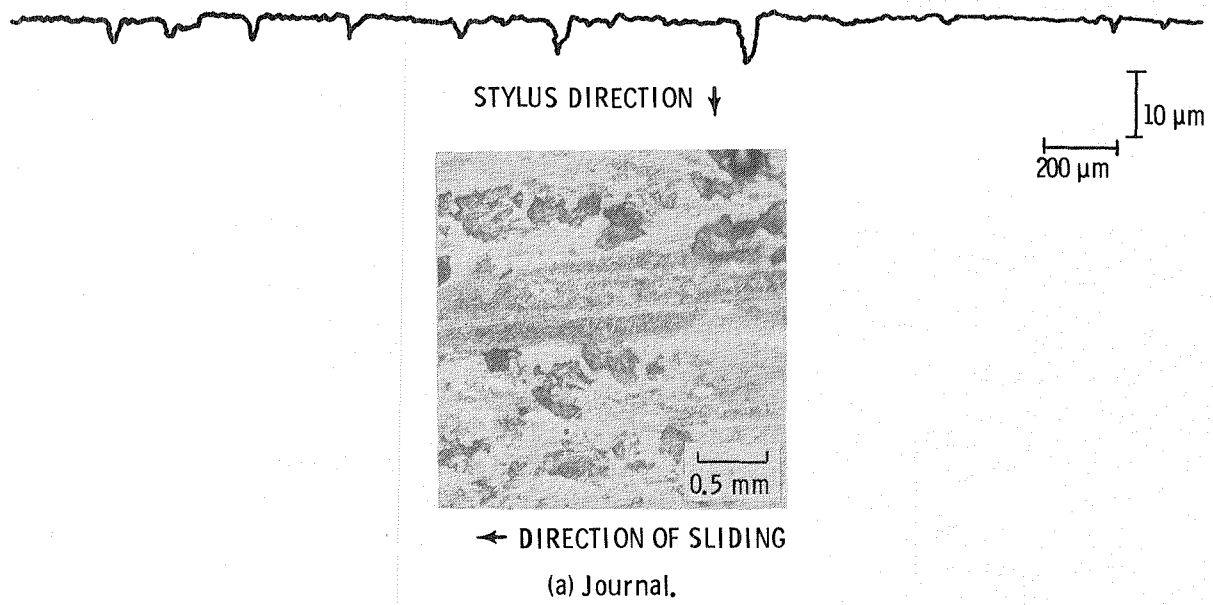


Figure 9. - Photomicrographs and surface profiles of journal coated with plasma-sprayed Cr_3C_2 - NiAl and preoxidized foil bearing after 4500 start/stop cycles. (Surface profiles are 90° to sliding direction.)

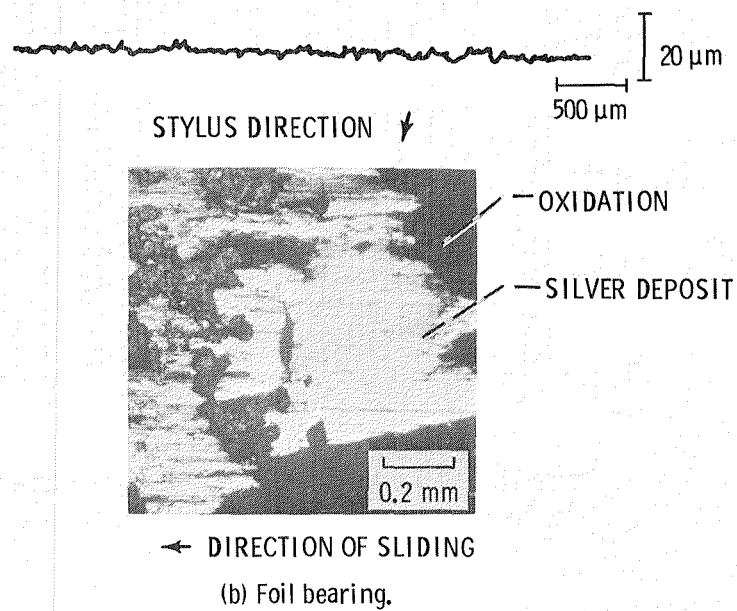
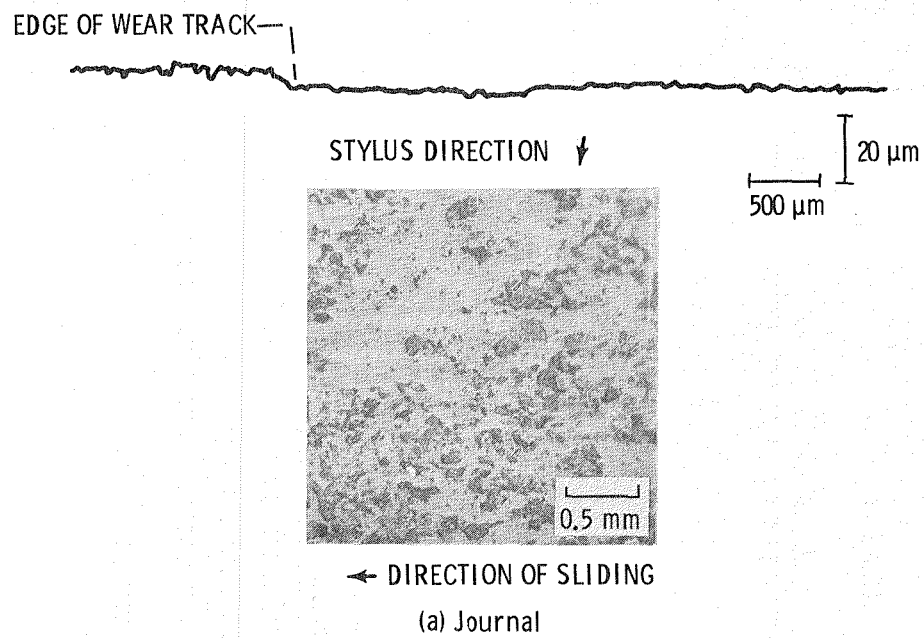


Figure 10. - Photomicrographs and surface profiles of journal coated with PS-200 and preoxidized foil bearing after 9000 start/stop cycles. (Surface profiles are 90° to sliding direction.)

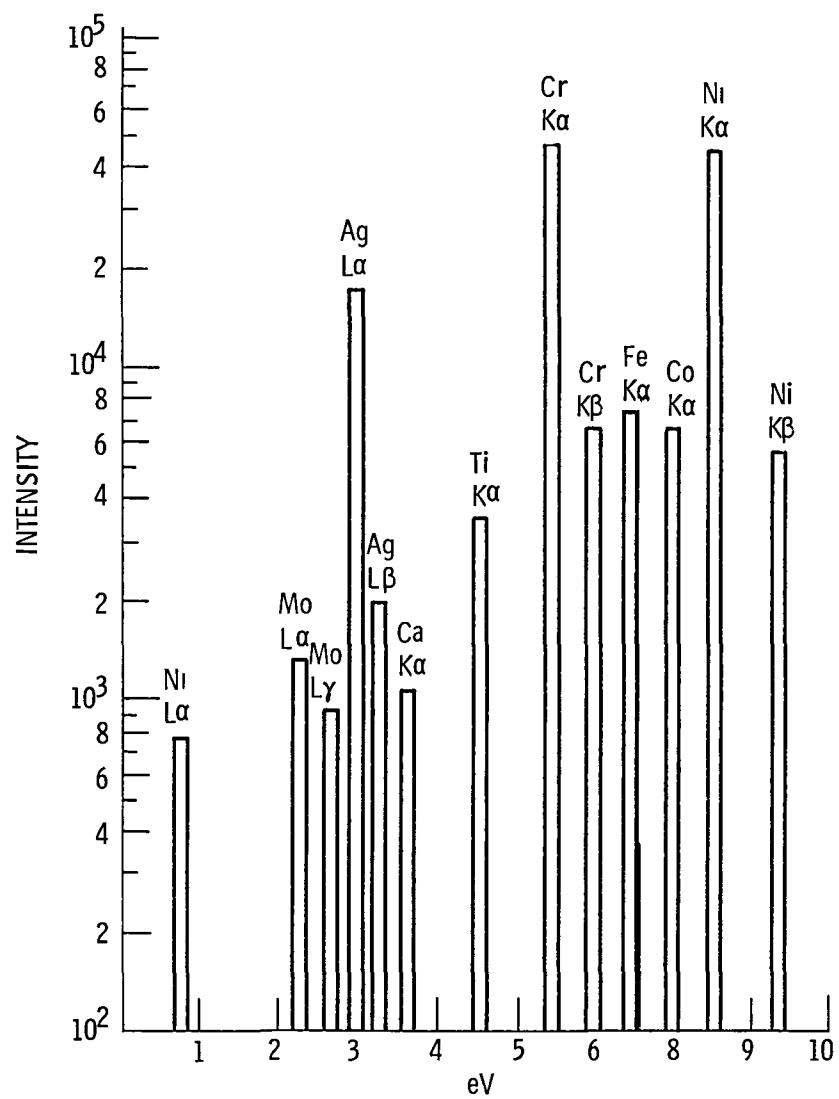


Figure 11. - X-ray spectrum of smooth foil surface against PS-200 coated journal after 9000 start/stop cycles.

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16 Abstract <p>A new self-lubricating coating composition of nickel aluminide-bonded chromium carbide formulated with silver and Group II fluorides was developed in a research program on high temperature solid lubricants. One of the proposed applications for this new coating composition is as a wide temperature spectrum solid lubricant for compliant foil gas bearings. Friction and wear properties were obtained using a foil gas bearing start/stop apparatus at temperatures from 25 to 650 °C. The journals were Inconel 718. Some were coated with the plasma sprayed experimental coating, others with unmodified nickel aluminide/chromium carbide as a baseline for comparison. The additional components were provided to assist in achieving low friction over the temperature range of interest. Uncoated, preoxidized Inconel X-750 foil bearings were operated against these surfaces. The foils were subjected to repeated start/stop cycles under a 14-kPa (2-psi) bearing unit loading. Sliding contact occurred during lift-off and coastdown at surface velocities less than 6 m/s (3000 rpm). Testing continued until 9000 start/stop cycles were accumulated or until a rise in starting torque indicated the journal/bearing had failed. Comparison in coating performance as well as discussions of their properties and methods of application are given.</p>					
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